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INTEGRATED DIGITAL TWIN AND GEO-FUSION FOR POST-MINING GEOMONITORING: SUBSURFACE MODELLING AND REMOTE SENSING APPLICATIONS

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Abstract

Post-mining landscapes present significant environmental and geotechnical challenges due to long-term impacts of underground exploitation, such as ground deformation, subsurface instability, and environmental degradation. Conventional monitoring methods often fall short due to a lack of surface indicators of underlying geological structures. Thus, accurately identifying subsurface discontinuities—such as faults, cavities, and weakened zones is essential for effective environmental risk assessment and sustainable land-use planning.

Previously, these challenges were approached using traditional surveying methods, which often lacked precision and were time-consuming. In this study, we introduce an innovative methodology utilizing MOVE software for comprehensive 3D geological modelling and UAV multispectral surveys to acquire detailed surface data. The process is complemented by rigorous field validation, involving the integration of geological, tectonic, and mining maps with borehole logs and seismic profiles.

Our results confirm the presence of persistent subsurface discontinuities in historically mined areas, often aligned with tectonic structures, subsidence lakes, and vegetation stress zones. This enhanced mapping of geological discontinuities and the comprehensive stability analysis of embankments demonstrate the methodology's potential to improve geomonitoring accuracy. Furthermore, our framework supports the development of dynamic digital twin models for predictive modelling and environmental risk management.

Overall, this integrated approach offers a robust and transferable methodology for addressing subsurface challenges in post-mining and similar environments, ultimately enabling more informed decision-making and long-term planning in areas affected by legacy mining activities.

Keywords: digital twin, post-mining, 3D subsurfaces modelling, remote sensing, UAV

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1. INTRODUCTION

The enduring environmental and geotechnical repercussions of underground mining activities on post-mining landscapes present a complex web of challenges [1,2]. Long-term impacts, such as ground deformation, subsurface instability, and broad environmental degradation, necessitate sophisticated monitoring approaches. Conventional techniques often fall short, primarily because the surface frequently lacks discernible indicators reflecting the underlying geological structures. Precisely identifying subsurface discontinuities, such as faults, cavities, and zones of weakened rock mass, is essential for robust environmental risk assessment and sustainable land use strategies.

Integrating remote sensing data into 3D geological modelling offering unprecedented accuracy and detail. The increasing accessibility of diverse geospatial data sources—LiDAR, SAR/InSAR, hyperspectral and multispectral imagery, UAV-derived photogrammetry, and geophysical surveys—empowers researchers to construct detailed models of both surface and subsurface structures [3]. These models are crucial for applications ranging from environmental monitoring and mining operations to civil engineering and hazard assessment.

Among the most effective tools, airborne LiDAR generates high-resolution digital elevation models (DEMs), even in dense vegetation. When combined with photogrammetry and geophysical data, LiDAR reveals subtle topographic variations indicating geological structures like faults and fracture zones. Studies have highlighted the effectiveness of integrating LiDAR with soil analysis to identify microtopographic features linked to landslides or shallow soil deformation, which are vital for developing early warning systems in geomorphologically active post-mining areas [3].

The legacy of coal extraction has left significant impacts on both the surface and subsurface environments. Subsidence phenomena vary in magnitude and frequently extend beyond mined-out zones [4], as seen in the Ruhr region, where intensive mining caused substantial vertical displacements [5]. Even after mining ceases, ground movement persists due to factors like rock mass relaxation and mine water rebound, which contributes to soil saturation and groundwater contamination [6,7].

The concept of the Digital Twin represents a significant paradigm shift in how post-mining land management and geomonitoring are approached. Developed in alignment with the advancements of Industry 4.0 technologies, a Digital Twin integrates GIS, sensor networks, real-time data streams, and artificial intelligence (AI) into a continuously updating virtual replica of real-world conditions. This virtual representation allows for a dynamic and comprehensive understanding of the complex interactions within the post-mining environment [8,9].

Digital Twins are not static models; rather, they are adaptive systems with the capability to run predictive simulations [10]. This functionality makes them invaluable as real-time decision-support tools for a diverse range of stakeholders, including city planners, environmental authorities, and mining regulators. These virtual systems also facilitate scenario modelling for potential future risks such as flooding, as well as opportunities for habitat restoration and land repurposing in the context of climate adaptation policies. Such advanced systems are already being utilized for long-term post-mining risk management in the Ruhr area and in other regions facing similar challenges.

A prime example of this innovative approach is the "Digital-Twin - Integrated Geomonitoring" project, which focuses on the closed Prosper-Haniel coal mine. This project aims to develop a robust research methodology for geomonitoring post-mining processes by effectively integrating modern research methods, advanced equipment, and sophisticated instruments. The project leverages a wide array of data sources, including valuable satellite observations from both the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA), as well as data acquired from dedicated drone flights and comprehensive geological and mining data collected throughout the entire operational lifespan of the mine [9].

A crucial component of this project involves the development of detailed three-dimensional rock mass models. These models are constructed using historical mining maps, geological surveys, and extensive borehole reports, providing a foundational understanding of the subsurface geological structure. The process of modelling yields critical knowledge about the geological framework, and modern mobile GIS tools are employed to verify the accuracy of these models and to meticulously document any changes occurring on the Earth's surface.

The "Digital-Twin" project is fundamentally based on the principles of the "Industry 4.0" concept, ensuring that every process within the project, from initial conceptualization to implementation, management, and the eventual closure and post-mining phases, is digitally monitored and managed. A key aspect of this approach is the complete digital implementation of all relevant data pertaining to the mine's entire life cycle, including the concession process, the extraction of raw materials, the closure procedures, and the subsequent post-mining phase. The continuous monitoring of the mining area is recognized as an essential element for achieving a comprehensive understanding of the post-mining processes at play. This thorough understanding allows for the identification and analysis of critical post-mining aspects and their effects, which can then be used to inform and potentially refine earlier stages of the mine's life cycle [9].

2. DESCRIPTION OF THE STUDY AREA

2.1. Geographical Overview

The study area encompasses the northern mining sections of the decommissioned Prosper-Haniel coal mine in the north west Ruhr region (Germany) (Figure 1). The area lies between the Emscher and Lippe valleys and includes the municipalities of Hünxe, Dinslaken, Oberhausen and Bottrop. It spans an area of approximately 10 km by 10 km. The northern and western boundaries are marked by the Schlägersheide and the Hünxer Wald, while the eastern boundary includes the Grafenwald and the Hohe Heide.

Coal mining in this area has deep historical roots. Operations began in the southern part of the study area in the 1960s, during a time when the German coal industry was under increasing economic pressure due to the coal crisis [11]. In response, the management of the Prosper-Haniel colliery—later consolidated from several smaller operations—was compelled to implement modern, efficient mining techniques to remain competitive. These technological and organizational improvements enabled the colliery to grow into the most modern shaft mining facility in the Ruhr region.

Over the following decades, mining activities expanded progressively northward, transitioning from the densely built-up urban zones of Bottrop into the more sparsely populated rural landscapes of the Kirchheller Heide. This shift not only altered the spatial dynamics of mining but also had significant implications for land use and surface morphology.

Today, the area is primarily characterized by agricultural land use, which is significantly influenced by the legacy of extensive underground mining networks. These have left lasting subsurface deformations and hydrological impacts. Additionally, the region includes areas affected by surface mineral extraction, especially for sand and gravel mining, which continues to shape the landscape (Figure 1).

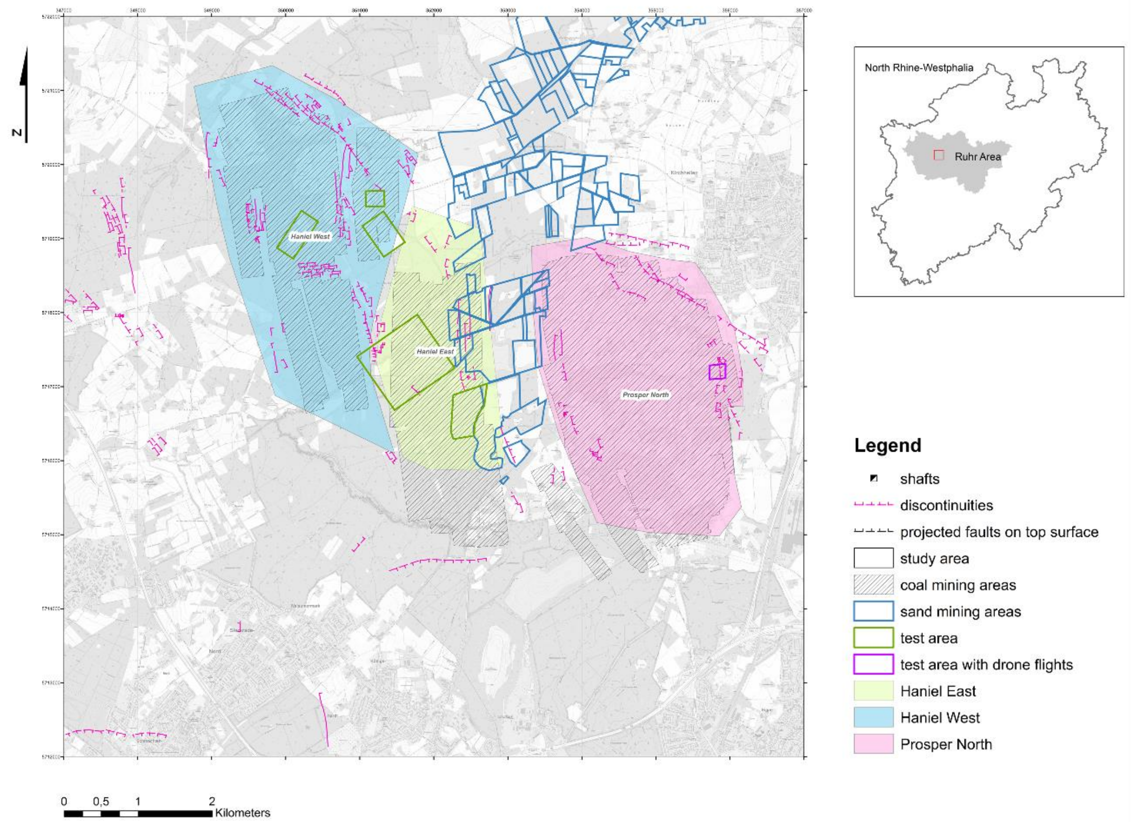

Fig. 1. Location of the research area – coal mining site Prosper-Haniel in Germany. Source of data [12,13]

2.2. Geological Overview

The study area encompasses the northern mining sections of the decommissioned Prosper-Haniel coal mine in the north western Ruhr region (Figure 1). It is bordered to the west by the Lohberg Horst, adjacent to the Hünxer Fault, which merges into the Drevenacker Fault. East of the Lohberg Horst lies the Hünxer Graben, bounded to the east by the west-dipping Franz-Haniel Fault. With a slight bend, the Franz-Haniel Fault also converges into the Drevenacker Fault (a lateral displacement zone). Further east lies the Gartrop Step Fault, characterized by a series of successive normal faults. Beyond this, the Grafenwald Horst follows, which is bounded by the Krudenburg Fault to the west and the Kölner-Bergwerksverein Fault (KBV Fault) to the east. The KBV Fault forms the eastern boundary of the study area and also converges with the Drevenacker Fault in its north western extension. Some of these faults extend into the overlying Cretaceous strata, and the Drevenacker Fault remained active during the Tertiary period [14,15].

In the hanging wall, the Upper Carboniferous, encountered at a depth of approximately 600 meters, is overlain by a thickening overburden. The overburden comprises stratigraphic units from the Permian, Triassic, Cretaceous and Tertiary periods [16]. The boundaries of the Zechstein (Permian) and the Buntsandstein (Triassic) run across the study area. The Zechstein sediments, the oldest overburden unit, consist of a sequence of evaporitic deposits, increasing in thickness towards the north. The Zechstein lies unconformably atop the Upper Carboniferous and is distributed along fracture tectonics north of the Gladbecker thrust fault.

The overlying Triassic is limited in the study area. The oldest Cretaceous deposits are represented by glauconitic fine and medium sands of the Olfen Formation [17]. Despite lithological variations, these sands frequently consist of greenish, silty-clayey sandy marlstone. In the eastern part of the model, it lies unconformably atop the Carboniferous surface. Above it, the Essen Greensand Formation is followed by the Baddeckenstedt and Brochterbeck Formations. The Turonian succession includes the Büren Formation, which was identified in only a few boreholes within the study area.

The overlying Coniacian is composed of white to grey calcareous marlstones of the Erwitte Formation, whose upper boundary marks the Middle-Coniacian limit, transitioning to the younger Emscher Formation. The Emscher Formation features marly facies, consisting of silt and calcareous marlstone. In the Upper Coniacian, it commonly transitions into uniform clayey marlstone layers. The Emscher Formation continues into the Middle Santonian before giving way to the Recklinghausen Formation, which consists of alternating sand-silt layers with weakly glauconitic sandy marls or marlstones. The thickness of the Recklinghausen Formation is estimated at 75–90 meters, though distinguishing it from the Emscher Formation is often challenging due to their similar lithological and colour characteristics.

The Bottrop basin was filled with unconsolidated fine and medium sands, including the Osterfeld Subformation (part of the Haltern Formation) and the Bottrop Formation, marking the end of the Cretaceous sequence in the study area.

The Tertiary deposits are present predominantly in the western part of the study area, outcropping in the southern and central sections. Their distribution is closely tied to fault-tectonic conditions and includes the Walsum Subformation, the Ratingen Subformation and Lintfort Subformation.

The Oligocene and Cretaceous layers near the surface are often only covered by thin Quaternary sediments, a few decimetres to meters thick. These consist largely of clayey-sandy ground moraines, terrace sediments from the Rhine, and glacial ice or meltwater deposits from cold periods. In the west, the Quaternary sediments are thinner, while in the east, aeolian sand deposits overlay the valley sands more extensively.

3. METHODOLOGY

Modern geological research increasingly relies on advanced technologies to better understand the complexity of Earth's structures. This study presents a precise methodology for integrating a three-dimensional geological model with data obtained from Unmanned Aerial Vehicles (UAVs). This method is designed to accurately identify and analyze tectonic discontinuities, which are crucial for assessing geological stability and potential seismic hazards. The main objective is to evaluate the effectiveness of combining UAV-derived data with a 3D geological model specifically for tectonic discontinuity identification (Figure 2). The aim is to establish a reproducible workflow and assess its applicability in geological hazard analysis.

The process begins with the preparation of all necessary input data. This includes a 3D geological model based on geological datasets such as geophysical profiles, borehole logs, and geological maps, as well as UAV-derived data. UAVs equipped with high-resolution and multispectral cameras perform surveys over the study area, capturing aerial images. The multispectral and hyperspectral cameras, with specific spectral ranges, are crucial not only for vegetation analysis but also for detecting geological features based on their spectral signatures.

Captured aerial images undergo processing, including image alignment, point matching, and generating of a dense point cloud, followed by the creation of a digital surface model (DSM) and orthophoto mosaics. The multispectral and hyperspectral cameras, which operate across specific spectral ranges, are crucial not only for analyzing vegetation by assessing health and stress indicators but also for detecting and characterizing geological features through their distinct spectral signatures. These cameras can capture data beyond the visible light spectrum, allowing for the differentiation of various minerals and rock types based on how they reflect or absorb particular wavelengths. This capability enables the identification of lithological variations, the detection of alterations due to hydrothermal processes, and the mapping of specific mineral compositions. By leveraging these spectral insights, researchers can gain a deeper understanding of the subsurface geological conditions and potential geological hazards, enhancing the accuracy and comprehensiveness of geological surveys.

After the UAV collected the aerial data, we proceeded to integrate this information with an existing geological model. This integration uses a shared coordinate reference system, which ensures all data aligns correctly in the same spatial framework. We performed this task in a GIS and 3D modelling environment, allowing us to seamlessly combine the surface data acquired from the UAV with detailed subsurface geological structures. This fusion results in a single, coherent geospatial model that serves as a comprehensive foundation for further spatial analysis and interpretations of geological phenomena.

During the analysis phase, we focused specifically on identifying tectonic faults. This was accomplished by carefully examining orthophotos generated from the UAV data. The orthophotos were scrutinized for linear features indicative of tectonic activity, such as distinct fault traces, abrupt changes in the surface texture of the land, and variations in vegetation patterns or topographic features. Such features often reflect underlying tectonic disruptions and are critical indicators of geological instability.

We chose orthophotos as the primary interpretive layer due to their high clarity and ease of visual analysis. They provide a detailed, contrast-rich view of the terrain, which is crucial for accurately identifying fault lines and other tectonic features. In contrast, we utilized point clouds as supplementary data. The point clouds primarily supported the validation of topographic details and facilitated detailed 3D visualization, helping to reinforce and verify the observations made from the orthophotos.

The identification of tectonic faults involves specific key criteria: the visibility of linear features, the contrast between different elements in the image, and the consistency of these features with known tectonic patterns. By adhering to these criteria, we enhanced the reliability and accuracy of fault detection.

To validate our methodology, we compared the tectonic features identified in our analysis with existing geological maps and fault traces confirmed through field surveys. This validation process involved overlay analysis in the GIS environment, allowing us to measure the spatial accuracy by assessing positional deviations, overlaps, and spatial congruence between our interpreted features and known geological data. This quantitative assessment informed us of the precision and reliability of our fusion and analysis methods, ensuring our approach could effectively contribute to understanding geological stability in the region.

Fig. 2. Visualisation of the workflow of the research

3.1 Geological Subsurface Modelling of the Overburden

The subsurface in the study area has been explored since the mid-1960s using deep boreholes and later through seismic measurements. In the course of mining activities, the underground was surveyed using mining surveying techniques [18]. However, the findings primarily remained with the mining operators or were submitted as mining survey documents to regional mining authority of the Arnsberg district government. Some of the data, however, is also available to the Geological Survey of North Rhine-Westphalia (GD NRW). In the digital coal seam archive, which derived the Coal Reserve Calculation (KVB) and later the Structural Model of the Upper Carboniferous (Strukturmodell Oberkarbon – SMOK) using numerical models.

Since there are hardly any more reliable geological data about the deeper subsurface in the Ruhr area than the early exploration and mining survey data, this represents a valuable data basis for geological subsurface modelling in this research project. Existing mining plans, structural maps, and contour line representations were georeferenced, digitized, and revaluated in conjunction with additional geophysical drilling data.

To represent a connection between the subsurface model and surface change processes, the mine workings (fields, key tunnels, and open shafts) were recorded in three dimensions. Additionally, subsidence over an area was calculated to indirectly analyse the relationship between mining activities and observed subsidence. This was necessary because only ground movements were available as open geodata [12].

As a critical foundation for overburden modelling, data from the Database for Exposures and Drillings were used (DABO NRW). The database provided approximately 2.000 drilling points for the study area with varying qualitative and quantitative stratigraphy information. These had to be revaluated for the modelling.

For large-scale modelling of tectonic conditions, regional or superregional model data (e.g., NRW 3D state model, Structural Model Upper Carboniferous) were not used. Given the model size and low resolution, they proved impractical. Detailed fault courses were obtained from mining survey structural maps and base plans for various depths (levels). These were compared with tectonic maps for the Lipper Main Syncline (1980) and Dorsten Main Anticline (1988) and correlated with existing 2D profiles. Furthermore, much of the available mining survey profiles from the Geological Survey NRW's digital coal seam archive could be spatially and vertically located. Several depth-converted 2D seismic profiles and interpreted profiles were integrated to enable a high-resolution three-dimensional representation of the overburden:

- 61 2D seismic profiles
  (e.g. Lohberg 1952, Kirchhellen 1953, Bottrop 1957, Nordlicht 1958, Prosper-Haniel 1975, Schermbeck 1981)
- 40 mining survey profiles
  (from Prosper-Haniel and Nordlicht mines)
- 19 hydrogeological profiles
  (HK10, HK25)
- 35 deep tectonic profiles
  (Dorsten Main Anticline, Emscher Main Syncline) [19,20]
- 14 engineering geological profiles
  (4406 Dinslaken, 4407 Bottrop).

The distribution and thickness information were derived from explanations of the geological maps:

- Geological Map NRW 1:25.000 – 4407 Bottrop [21],
- Geological Map NRW 1:25.000 – 4406 Dinslaken [22], and
- Data and explanations from the mapping project “Ruhrgebiet” [23].

For the temporal analysis of subsidence calculations and for detecting surface irregularities, LiDAR data were used. GeoBasis NRW provided periodic raw data for the study area. These data were processed and resampled with a spatial resolution of 10 m by 10 m. The flight periods covered the years 1996, 2000, 2005, 2010, 2014, and 2020. To reconstruct the original ground surface, contour lines from the Prussian primary survey of 1897 were vectorized from subsequent topographic maps:

- Topographic Map NRW 1:25.000 – 4306 Hünxe (1931),
- Topographic Map NRW 1:25.000 – 4307 Dorsten (1926),
- Topographic Map NRW 1:25.000 – 4406 Dinslaken (1964), and
- Topographic Map NRW 1:25.000 – 4407 Bottrop (1926).

Additionally, geological and engineering geological profiles were available due to geological mapping of map sheets 4406 Dinslaken and 4407 Bottrop at a scale of 1:25.000.

The subsurface reconstruction methodology was based on 3D deposit modelling, enabling spatial positioning of legacy 2D geological data in three dimensions. Using both horizontal coordinates and depth information, mine workings were reconstructed three-dimensionally together with stratigraphic context. For this purpose, the software MOVE (v2018.0.1) was employed, supporting integrated fault and horizon modelling as well as validation procedures.

The initial focus was on tectonic conditions because faults in the subsurface form barriers for geological horizons. Areal fault structures influence the model geometries and significantly increase the complexity of the geological 3D model. For the fault model, the mentioned mining survey profiles were first recorded as intersection lines along the cross-sections or directional sections. The profile representations were then imported as vertical image files and oriented both vertically in depth and horizontally along the length of the cross-section. The vertical fault courses could now be captured in the profiles. Together with the base plans, the vertical courses from the profiles were combined with the horizontal courses in the plans. The captured structures also allowed conclusions to be drawn about fault properties. Combining both sets of information ultimately enabled the fault surfaces to be modelled. During the 3D fault reconstruction, flat-lying thrusts were also modelled in addition to known normal faults.

In addition to faults, different profile types were recorded. Mining survey profiles and 2D seismic data, in particular, provided essential insights into the depth location of the overburden and the distribution of Zechstein and Buntsandstein. The large number of profiles allowed the generation of a 3D line model (3D fence) for each relevant horizon. After analysing all profiles, borehole data queries were made to the NRW borehole database. After evaluating the stratigraphy, distribution, and thickness, borehole information for the relevant horizon was transferred as 3D borehole markers into the 3D application. For step-by-step validation of spatial location and modelling, the outcrop boundaries (distribution) to the overlying horizon were also included to create a coherent subsurface model.

The different age positions of the horizons often lead to uncertainties in geological models, which vary depending on complexity and variety. Quaternary stratigraphy is often comprehensively documented through shallow drilling, field investigations, and sampling. However, due to minor thicknesses and varying litho-facies differences of the substrates, geological 3D models rarely represent near-surface horizons. Therefore, the subsurface model was limited exclusively to the structures and composition of the deeper overburden horizons.

3.2 Satellite Remote Sensing

The selection of sensors and data acquisition is an important project phase when using satellite remote sensing data, as the results to be achieved depend directly on this. Therefore, criteria should be established before starting data acquisition, based on which the data can be evaluated for its suitability for the project [24]. The data sources for the research project included satellite images from the Landsat (NASA) and Copernicus (ESA) missions.

In Pawlik et al. [24], the following criteria are proposed (based on [25,26]):

- Timeframe: The time series covers the period from April 1984 to August 2022 (missions: Landsat 4, 5, 8, 9, and Sentinel-2).
- Temporal resolution: The revisit rate is 16 days for Landsat 4, 5, 8, and 9, and 5 days for Sentinel-2.
- Spatial coverage: The spatial coverage is defined by the study area. The study area does not fall into the overlap region of two overflight orbits.
- Spatial or geometric resolution: The spatial or geometric resolution is the measure of the smallest object that a sensor can distinguish. The spatial resolution is 30 m to 120 m for Landsat 4 and 5, 15 m to 100 m for Landsat 8 and 9, and 10 m to 60 m for Sentinel-2.
- Spectral resolution: The spectral resolution specifies how many spectral bands a sensor can simultaneously capture. Landsat 4 and Landsat 5 provide 4 (Multispectral Scanner - MSS) and 5 (Thematic Mapper - TM) bands, Landsat 8 and Landsat 9 provide 11 bands, and Sentinel-2 provides 13 bands.
- Cloud coverage: Due to cloud cover, only satellite images with minimal coverage were selected. This generally reduces the availability of optical satellite data in Central Europe.

Data acquisition begins after selecting suitable scenes and cropping them to a specific study area. Subsequently, an appropriate evaluation method is selected and adapted to the research question. Indicators are typically used, where data from different spectral channels are processed to gain insight into specific aspects. The use of indicators has the advantage of quickly processing many scenes over large areas. For example, chlorophyll plays a significant role when analysing vegetation health. Chlorophyll absorbs energy at certain wavelengths to generate carbon for plant growth through photosynthesis. However, to prevent plants from overheating, specific energy-rich (red) wavelengths are reflected [27]. The Normalized Difference Vegetation Index (NDVI), developed by Rouse et al. [28], allows the observation of vegetation health. The NDVI is based on bands in the red and near-infrared regions of the spectrum. The index represents values ranging from -1 to 1. According to the classification presented by Kuechly et al [27], red colours correspond to plots of land, roads, buildings, and water. Green colours represent vegetation – lighter shades indicate poorer vegetation health, while darker shades indicate very good vegetation health. Post-mining transformations in the subsurface often evolve slowly and cumulatively over long periods. Subsidence, surface rebound, or re-compaction of overburden can manifest years after mining activities have ceased. Therefore, the analysis of long-term vegetation trends, using NDVI or similar indices, provides an indirect means to monitor these slow processes.

This approach is particularly useful in areas where open-access geodetic data are limited or absent. For this reason, the temporal dimension of satellite datasets was critical in this study. The time series spans more than three decades, capturing both the active mining phase (1970s–2018) [11,12].and the post-mining transition, enabling comparison between vegetation recovery and potential ground instabilities across time. By systematically analyzing changes in vegetation health over this multi-decadal timeline, it becomes possible to infer zones of ongoing surface instability, detect ecological stagnation, or confirm revegetation success in reclaimed mining areas.

3.3 Drone Surveys

The characteristics of drone flights encompass numerous technical, operational, and regulatory aspects that define their use and capabilities. Drones are increasingly equipped with advanced navigation systems such as GNSS (Global Navigation Satellite Systems), including GPS (Global Positioning System) to determine their position accurately, which is essential for autonomous flights and terrain mapping. They are also equipped with sensors used for capturing visual data and creating 3D terrain models.

In geological research, drones have become an indispensable tool due to their ability to conduct detailed investigations in areas that are either difficult to access or would otherwise require significant time, personnel, and resources. Their compact size, manoeuvrability, and ability to fly at low altitudes allow for safe and efficient data collection in complex terrains, including steep slopes, mining pits, landslide zones, and other hazardous or remote environments [29]. Drones used in this study were equipped with a range of sensors, including optical, multispectral, hyperspectral, and thermal cameras, enabling the collection of diverse datasets tailored to different geological applications. Optical sensors allow for the acquisition of high-resolution imagery, which is used to create orthophotos and three-dimensional terrain models through photogrammetric processing. These products provide accurate representations of surface structures, enabling the identification of geological features such as faults, folds, fracture zones, and sedimentary layering [30].

Multispectral and hyperspectral sensors extend the analytical capacity by capturing data beyond the visible light spectrum. They enable the differentiation of mineral compositions, the detection of vegetation stress linked to underlying geology, and the mapping of surface materials based on their spectral signatures [31]. These capabilities are particularly useful in lithological classification, mineral exploration, and environmental monitoring in post-mining landscapes.

The integration of data from these various sensors is essential for achieving a comprehensive understanding of the geological setting. By combining optical and spectral information, researchers can cross-validate interpretations, reduce uncertainty, and produce more robust geological models.

Moreover, repeated drone surveys allow for temporal analyses, enabling the monitoring of changes over time. These time-series datasets can reveal surface deformation, erosion patterns, slope instability, or sediment displacement. Such dynamic monitoring is particularly relevant in active or environmentally sensitive areas, where early detection of changes is critical for risk assessment and mitigation planning.

Overall, the use of drone-based remote sensing in geological research significantly enhances spatial accuracy, improves field efficiency, and opens new possibilities for high-resolution, multi-dimensional terrain analysis. The methodology applied in this study demonstrates the practical advantages of UAVs in capturing and integrating complex datasets essential for modern geological investigations.

3.4 Mobile GIS

A method for verifying data in the field is mobile GIS (mobile Geographic Information System), which is a technology for capturing, processing, and analysing geographic data using mobile devices such as smartphones, tablets, or specialized GPS devices. Mobile GIS systems integrate technologies for geolocation, mapping, navigation, and data processing, enabling real-time work with geographic data in the field. It allows users to collect geographic data directly in the field. The ability to update and synchronize data with a central database in real-time significantly increases the efficiency of fieldwork. This technology makes it possible to store photographic and audio-visual documentation, as well as descriptions of specific measurement points, within the application, allowing verification of the actual environmental conditions at a given location. As Nowak et al. [32] show, collecting location and descriptive information is an important component of fieldwork.

For this work, the concept for a geodata acquisition procedure proposed by Blachowski and Koźma [33] was implemented:

- Analysis of existing source material,
- Exploration of survey sites in the field,
- Selection of measurement techniques,
- Design of a data collection form for the database,
- Conducting field measurements,
- Processing of GNSS data (Global Navigation Satellite System), and
- Analysis, integration, and interpretation of data obtained from the measurements.

The integration with geographic information systems (desktop, workstation, server) then enables further processing, validation, and visualization of geographic data on interactive digital maps. Integrating data on the geological structure with field-acquired information in a GIS project allows for a comprehensive understanding and visualization of the geological properties at a specific location.

4. RESULTS

4.1 3D Model

The result of the overburden modelling lies above the Carboniferous deposit section. For this purpose, a total of 11 units were defined:

- Top of Terrain Surface
- Quaternary
- Tertiary
- Cretaceous
  - Bottrop Formation
  - Haltern Formation
  - Recklinghausen Formation
  - Emscher Formation
- Buntsandstein
- Zechstein
- Carboniferous

Furthermore, 3 thrust faults and over 35 faults (normal, reverse, and strike-slip faults) were modelled in three dimensions.

Figure 3 exemplarily shows an isolated view of the Krudenburg Fault. Along the illustrated fault surface (blue), several vertical fault sections (red) were identified using nine mining survey profiles and three 2D seismic lines. The fault's course was derived from the survey documents for the 5th level (-728 m DHHN) and the 6th level (-920 m DHHN). The identified elements were subsequently used for the interpolation of the fault surface.

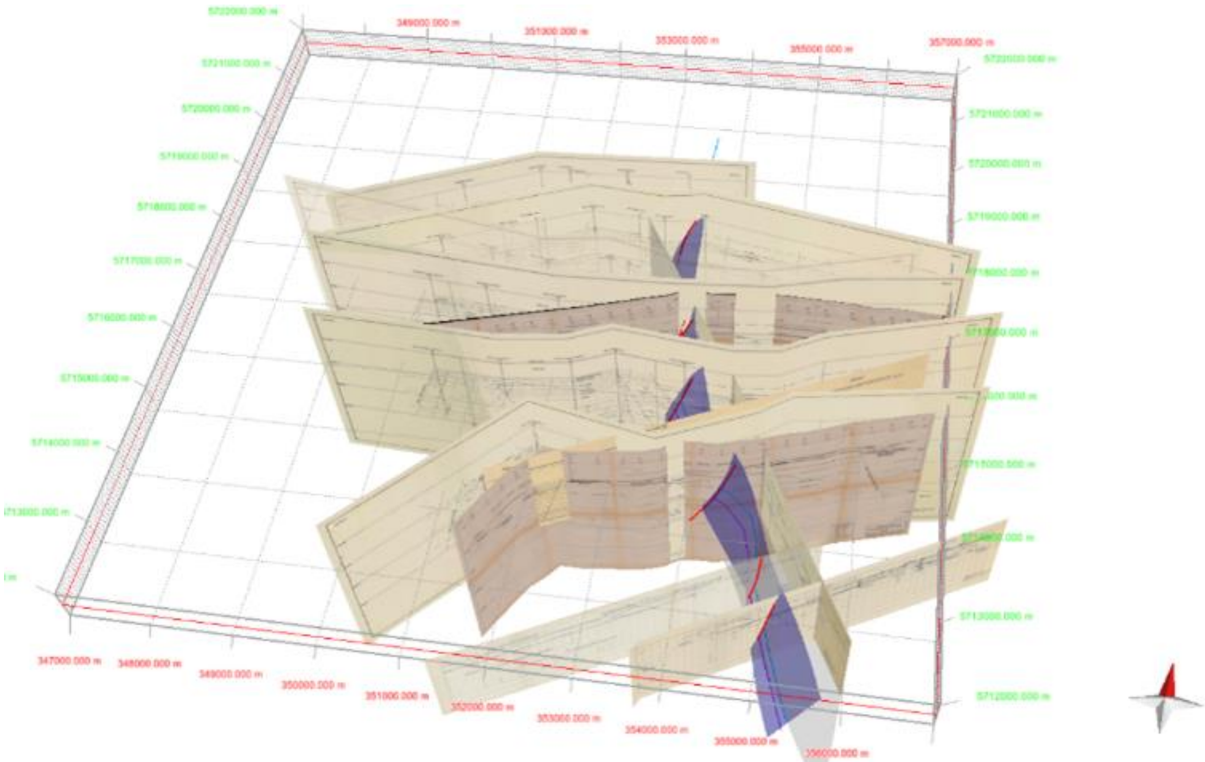

Fig. 3. Oblique view of the modelled Krudenburg fault on the basis of mine survey profiles

Figure 4 presents the overall result of the re-evaluated fault model. From the geodata, over 1,200 fault surface segments were interpreted, forming the backbone of the subsequent modelling work.

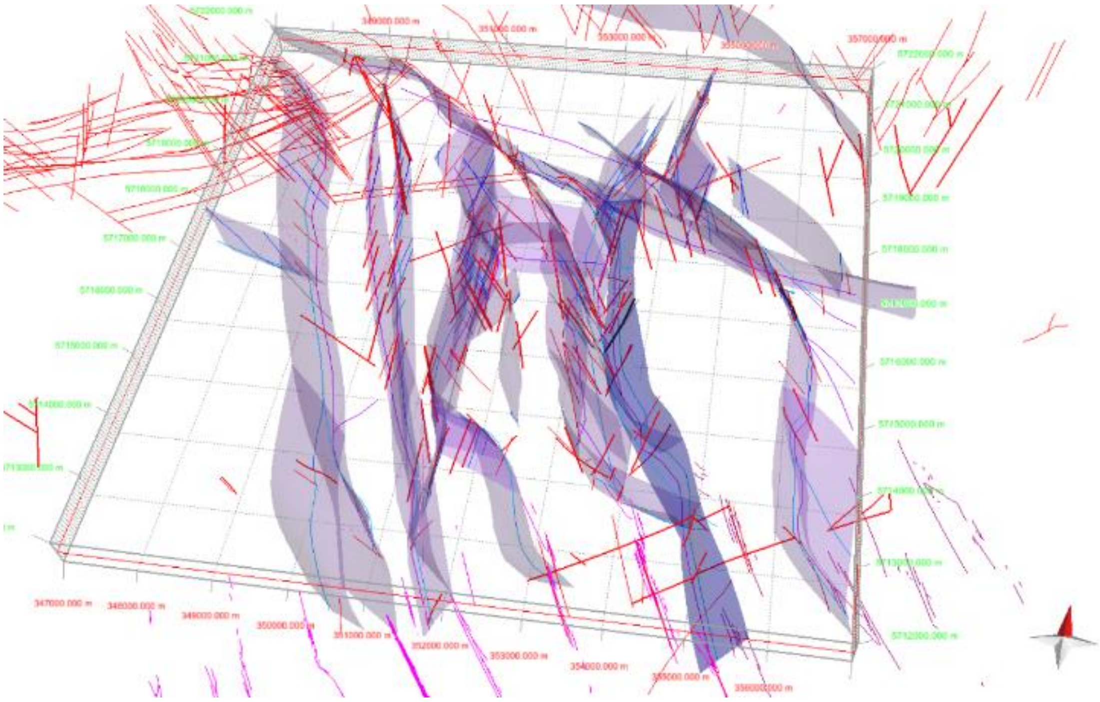

Fig. 4. Oblique view of the modelled faults in the research area

Figure 5 provides a view from the southeast of the schematic excerpt of the overburden model. The modelling was carried out successively from the younger to the older rock layers. In addition to the fault surfaces (blue), the model shows the Tertiary units (orange), the Cretaceous units of the Bottrop Formation (dark green) and the Haltern Formation (light green). The base of the overburden model is represented by the top of the Upper Carboniferous (gray). The figure highlights the geological complexity of the overburden, underscoring the need for further geodata fusion to achieve validation.

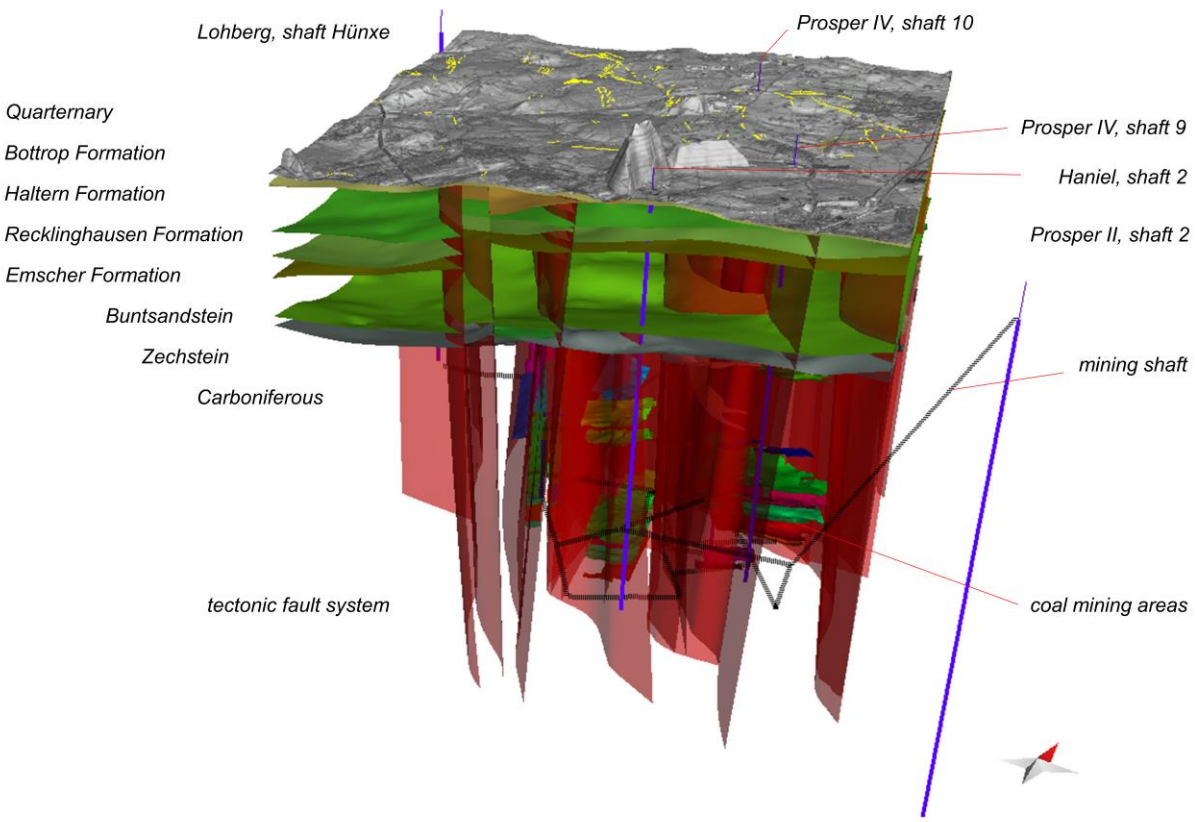

Fig. 5. Oblique view of the overburden model (Exaggeration: 7,5; looking NW) showing the faults (red), the coal mining areas (red, green), the top of the Carboniferous (grey), the upper formations of the overburden (green, orange) and the upper Quaternary below the top surface

4.2 Satellite Remote Sensing

The application of multispectral satellite remote sensing enables the construction of a long time series in the study area. A total of 165 scenes were selected, processed, and analysed for the satellites Landsat 4, 5, 7, 8, 9 and Sentinel-2. Various indicators were calculated for these scenes. Figure 6 presents an example time series for the study area (false-colour and optical images).

Based on the scene from 2000, taken during the active mining period, the overarching changes are essentially:

- Waste dumps: Halde Haniel, Halde Schöttelheide, and Halde Töttelberg (red frame),
- Subsidence lakes: Weihnachtssee, Pfingstsee and two unnamed subsidence lakes (blue frame),
- Surface-near gravel and sand extraction in the sand pits: Stremmer and Spickermann (yellow frame).

Detailed differences cannot be detected in the optical images. The influence on the surface caused by subsidence and potential discontinuities cannot be clearly identified. Therefore, the calculated NDVI is crucial for the change analysis (Figure 6).

The images show large-scale vegetation damage as red coloration of the NDVI in the areas directly influenced by mining activity. However, the images also illustrate that after the cessation of mining, an improvement in vegetation conditions occurred, for example, at the southern spoil heap.

A more detailed examination of vegetation damage concerning potential impacts along discontinuities is not possible due to the spatial resolution of the satellite sensors (Figure 7, E).

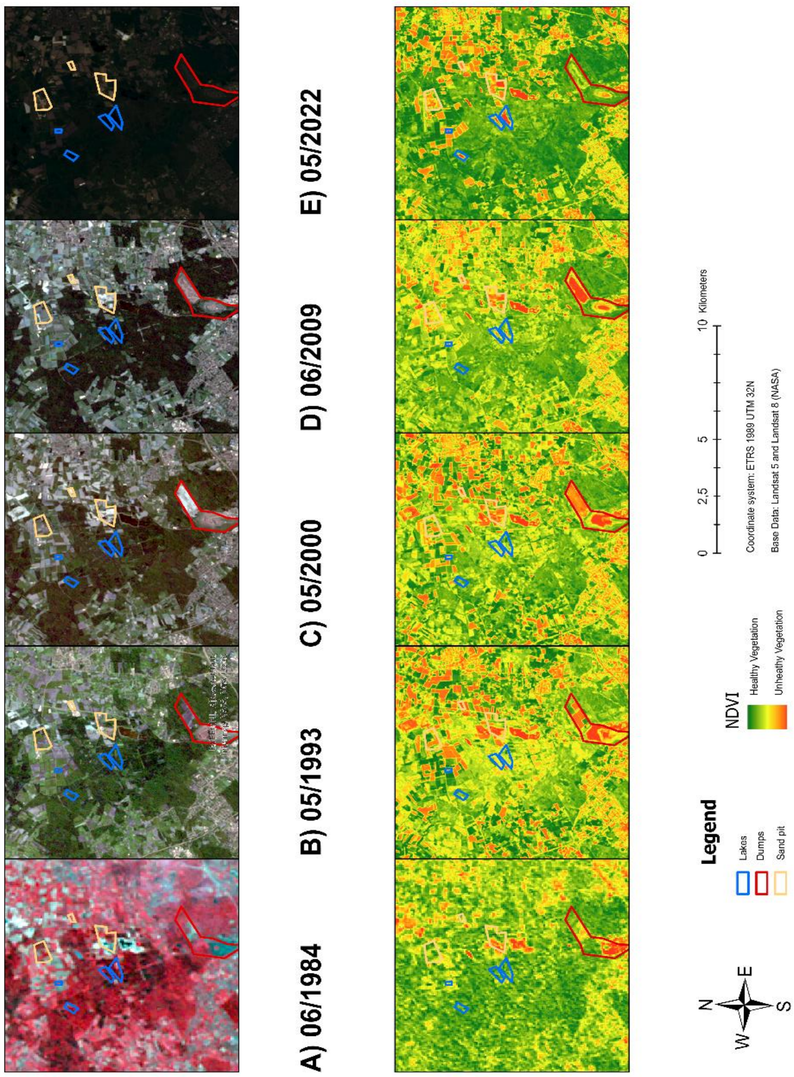

Fig. 6. Large scale changes in the research area between 1984 and 2022 and spatiotemporal analysis of the research area on the basis of the NDVI

4.3 Drones Surveys

As an example of additional detailed drone surveys in the study area, the results from optical and multispectral flights conducted on September 6, 2023, in Grafenwald are presented (Figure 7; A). In this study, a Digital Terrain Model (DTM) (Figure 7; B) and a Digital Surface Model (DSM) (Figure 7; C) were created to represent the terrain surface in a specific area. This enables the identification of locations subject to changes.

The use of multispectral drone imagery allows for the generation and visualization of an orthophoto map (Figure 7; A) and, as a derivative, the calculation of vegetation indices (e.g., NDVI - Figure 7; E), which enable monitoring of vegetation health. It is important to note that vegetation indices were originally calculated based on satellite images; however, as shown by Pawlik et al. [34], multispectral sensors used during drone flights have similar spectral bandwidths. Therefore, it is also possible to calculate vegetation indices using this data.

As illustrated in Figures 7 D and 7 E, the NDVI indicator shows different values depending on the pixel resolution of the respective image: for satellite missions, the resolution ranges from 10 m (Copernicus) to 30 m (NASA), whereas for drone flights, the resolution depends on flight altitude and varies within the centimetre range, depending on the sensor used.

By integrating the results of the geological structure modelling (shown in Figures 7 - orange colour), modelled terrain discontinuities on the Carboniferous surface can be verified through drone surveys (white colour) on the terrain surface. It is noteworthy that the digital terrain models (Figures 7 B and C) not only indicate changes in the area of discontinuities but also reveal changes through the application of the NDVI indicator.

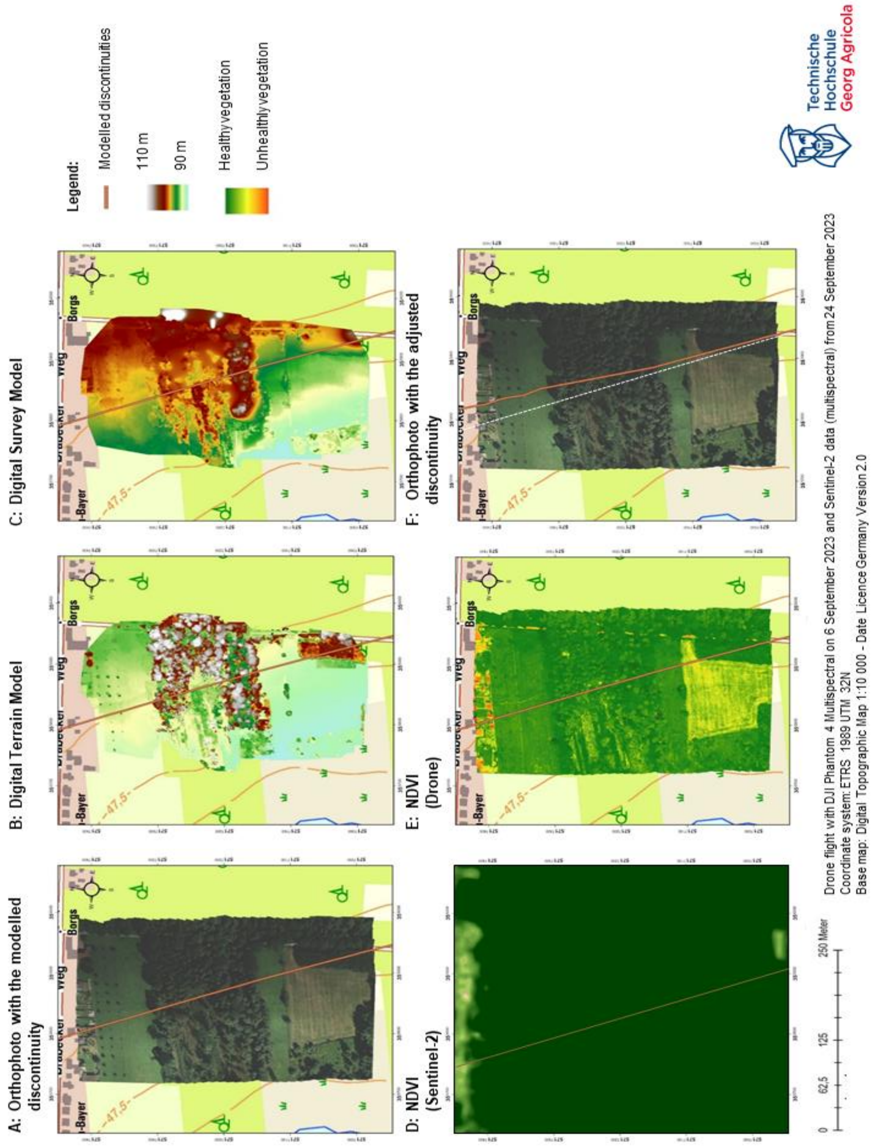

Fig. 7. Visualisation of the results of the copter flights in Grafenwald (A: Orthophoto with the modelled discontinuity, B: Surface model, D: Elevation model, D: Vegetation index NDVI (Sentinel-2), E: Vegetation index NDVI (Copter), F: Adjusted location of the modelled discontinuity)

4.4 Field work

As part of the validation, over 500 points were surveyed and documented across the entire study area. One method for validating the results is field measurements using mobile GIS, which allows for the collection of information and photographic documentation through a descriptive form, with the ability to mark the measurement point.

The integration of digital results with field validation demonstrates the potent synergy of combining technologies in geological studies. Utilizing drones for digital analysis (Figure 7) allowed for the identification of potential discontinuities through changes in vegetation and terrain elevation.

Advanced orthophoto maps and NDVI analyses enabled precise mapping of tectonic faults, providing high-resolution data.

Field validation in the Grafenwald discontinuity zone (Figure 8) revealed significant deviations from digital predictions, with faults observed approximately 50 meters further east. These on-site observations were crucial for refining models to ensure projections accurately reflect reality.

Nevertheless, limitations of this approach include potential interpretation errors due to restricted data resolution and uncertainties from terrain variability. To minimize these limitations, it is essential to employ thorough model calibration and regularly update field data. Implementing systematic validation methods, such as additional geodetic measurements and multispectral analysis, can further enhance interpretative accuracy.

Combining drone digital data (Figure 7) with field observations (Figure 8) allowed for the precise reproduction of actual conditions and alignment of theoretical models with field observations. Such an approach improves the reliability of geological assessments, crucial for effective risk management and land-use planning. The use of advanced digital tools coupled with rigorous field verification underscores how predictive and adaptive capabilities in post-industrial environmental management can be effectively enhanced.

Fig. 8. Detailed view of the application of mobile GIS to map the discontinuities in Grafenwald: Orange line modelled discontinuity (carbon surface), red line - discontinuity on the surface after validation with drone data (left) and in-situ documentation using mobile GIS (right)

The principal contributions of this research are characterized by the extensive integration of diverse data sources. The three-dimensional geological modelling has advanced the understanding of stratigraphic formations and fault mechanics, essential for accurate subsidence prediction. Furthermore, satellite and drone-based surveys have enabled sustained, high-resolution environmental monitoring, while rigorous field validation has provided necessary calibration for digital models.

Future directions propose the incorporation of real-time sensor data and the application of artificial intelligence, such as Convolutional Neural Networks (CNNs), to enhance fault detection precision and predictive modelling capabilities. Moreover, evaluating these methodologies across varied geographical and geological contexts will reinforce their generalizability and scalability. Promoting community involvement and transparency through accessible insights derived from the Digital Twin framework can significantly enhance decision-making in post-mining land management.

This comprehensive and integrated methodology marks a pivotal advancement in sustainable post-mining land governance, driven by sophisticated data integration and cutting-edge technological approaches.

5. DISCUSSION

The interpretation of the static overburden model provides new insights into the spatial configuration of stratigraphic formations and their thicknesses. This is a direct result of conducting a comprehensive three-dimensional modelling effort, a significant advancement over previous profile-line-based interpretations of initial exploration results. This 3D model allows for a more accurate spatial context for integrating surface and subsurface observations, which is crucial for understanding the long-term impacts of mining. Furthermore, the overburden model enables a detailed representation of fault positions that were geologically active only until the Cretaceous period. These faults were partially reactivated as weakness zones due to mining activities, manifesting as induced discontinuities at the surface. This spatial correlation between structural geology and of post-mining ground deformations is essential for effective risk assessment and land-use planning in the region. The move from 2D to 3D modelling, facilitated by software like MOVE, represents a substantial methodological improvement, offering a more accurate spatial context for integrating surface and subsurface observations.

The results obtained from the drone flights offer valuable high spatial-resolution data, as a crucial intermediary between lower-resolution but temporally rich satellite data. This enables detailed spatial-temporal analyses, allowing for the detection of small-scale changes in vegetation using indicators such as the Normalized Difference Vegetation Index (NDVI). The evaluation of high-resolution terrain models combined with the NDVI improves ~~in~~ the positional accuracy and determination of the location and course of a discontinuity in open land areas (Figure 7; F). This NDVI-based monitoring not only captures vegetation stress but can also serve as an early-warning indicator of ground instability linked to subsurface deformation. This highlights the role of vegetation indices as proxy variables in environmental diagnostics in post-mining landscapes...

The application of Mobile GIS is an indispensable for field verification method. On-site analysis of remains the most reliable way to validate changes observed in satellite and drone imagery. The detection of a displacement of up to 50 cm during the inspection of discontinuity (Figure 8), underscores the importance of ground-truthing for conforming remotely sensed observations. On-site inspections are particularly important in forested areas where tree canopies obscure the ground, preventing a clear view from aerial platforms. They are also critical for tracking small-scale changes, such as cracks and fissures in asphalt above discontinuities. Such field verification reinforces the reliability of remotely sensed observations and strengthens the feedback loop between field evidence and data interpretation workflows.

The foundation for geodata fusion in this study is the integrated reassessment of geodata for the overburden above the deposit section and the creation of a static geological overburden model. This is particularly important for differentiating the various overlapping effects observed at the surface, which include a high degree of underground mining activity, rapid subsurface extraction processes, tectonic inventory in the overburden, overlap of near-surface extraction operations, soils sensitive to subsidence due to changing climatic conditions, and strong seasonal fluctuations in the groundwater table. These interrelated phenomena complicate the causal attribution of ground movements, highlighting the necessity for integrated analytical frameworks. The model introduced here accounts for spatial superposition and temporal sequencing of deformation sources.

Given the complex interplay of mining-induced effects with geological, tectonic, and soil-related processes, large-scale geo- and environmental monitoring is necessary. This cannot be achieved solely through the legally mandated surveying measurements or surface damage inspections. The use of high-temporal-resolution multispectral satellite data provides tools for monitoring environmental changes. Early changes in vegetation, observable through NDVI, serve as critical indicators of subsurface changes, allowing for the coupling of subsurface and surface effects. These satellite-based insights form a cost-effective backbone for long-term surveillance but require supplementation by high-resolution UAV data to capture localized surface evolution.

However, full integration is only possible through the spatial-temporal intermediate layer provided by optical and multispectral drone flights and on-site inspections using Mobile GIS. As demonstrated in this research project, this approach allows for the detection and analysis of very small-scale changes at the surface. These results can then be fed back into the analysis of the overburden and the construction of the static geological subsurface model. The bidirectional data flow between surface measurements and subsurface modelling fosters a new level of interpretative synergy, strengthening dynamic scenario simulations in post-mining risk assessments.

The application of the digital twin concept traditionally involves a highly time-resolved coupling of processes in the digital and real-world environments. Nevertheless, constructing a simplified digital twin for the former Prosper-Haniel mine—combining subsurface modelling results with time series of surface observations—represents a significant step toward a better understanding of post-mining conditions. Although not time-synchronous, this digital twin prototype bridges historical geological knowledge with current terrain evolution and supports decision-making in post-mining management. The three-dimensional geological model of the decommissioned Prosper-Haniel mine provides information on the geology and tectonics of the study area. Meanwhile, multispectral satellite and drone data combined with mobile GIS ensure the spatial and temporal validation of the results. The integration of open geodata conducted in this research project, resulting in a digital twin of a former underground mine, forms the basis for future post-mining risk management. This approach is transferable to other former mining locations, both nationally and internationally. Such transferability highlights the scalability and adaptability of the workflow, making it a benchmark model for digital transformation in legacy mining contexts.

6. CONCLUSIONS

The research project "Digital Twin – Integrated Geomonitoring" addresses the complex challenge of monitoring and managing post-mining processes, focusing on the former Prosper-Haniel coal mine in the northern Ruhr region. The central problem lies in effectively integrating and interpreting diverse geodata to understand the impacts of historical mining activities on both surface and subsurface environments.

The study’s main achievements include the development of a geomonitoring concept through a comprehensive fusion of geodata, enhancing the understanding of stratigraphic unit distribution and fault lines. This methodology enables differentiation of ground movement processes, marking a first in the field. By combining traditional geological modelling with cutting-edge technologies such as multispectral remote sensing and mobile GIS, the study achieved heightened accuracy in predictive modelling and precise identification of surface discontinuities. The application of a modular Digital Twin framework illustrates considerable potential for post-mining risk management, offering adaptability and integration opportunities with urban planning and environmental protection efforts.

Despite these breakthroughs, the research faces limitations. The accuracy of the 3D geological model is reliant on the quality and availability of historical data, which can sometimes be inconsistent or incomplete. Remote sensing analyses are subject to challenges posed by vegetation cover and atmospheric conditions, which can obscure subtle subsurface changes. Additionally, the implemented Digital Twin remains a simplified prototype, lacking fully time-synchronized real-time predictive capabilities. While the study's methodology is transferable, its applicability might require adjustments to fit different geological and mining contexts beyond the Prosper-Haniel site.

Looking forward, the study suggests several avenues for further research. Enhancing the Digital Twin model with real-time sensor data and incorporating advanced AI and machine learning techniques could significantly improve its predictive capabilities. Exploring hyperspectral imagery and sophisticated image processing methods would allow better detection and characterization of minor surface changes indicative of instability. Comparative studies across various post-mining regions would help validate and refine the methodological approach, ensuring its wider applicability. Additionally, investigating the long-term ecological impacts and the effectiveness of land repurposing strategies informed by the Digital Twin framework would support sustainable management practices. Finally, increasing community engagement through improved public access to Digital Twin insights can promote transparency and facilitate informed decision-making in post-mining areas. This work represents a transformative step towards comprehensive, sustainable, and technology-driven stewardship of post-mining landscapes.

ADDITIONAL INFORMATION

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